Influence of moisture content on the mechanical properties of Guadua Culms

Influencia del contenido de humedad en las propiedades mecánicas de la Caña de Guadua

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Abstract

Introduction– Due to its earthquake behavior, the use of bamboo for structural purposes has increased in the latest decades, mainly in South American countries, in which, their employment, has been standardized in the design bases. However, for the efficient use of bamboo as a construction material, it is necessary to consider that being a natural material, volumetric variations can occur, especially when the material is subjected to changes in moisture between the saturation point of the fibers and the equilibrium moisture.

Objectives– The objective of this paper is to evaluate the influence of the moisture content on the mechanical properties of elements extracted from the bottom, middle, and top of bamboo culms.

Methodology– For the study, research is carried out with a quantitative approach. The experimental characterization was focused on the determination of compression, bending, and shear strength, according to the recommendations of the Colombian Technical Standards.

Results– Results allow verifying that bamboo elements are susceptible to vary their strength and stiffness depending on the equilibrium moisture of the region to be considered in the structural design.

Conclusions– The influence of the moisture content on the mechanical properties of elements extracted from the bottom, middle, and top of bamboo culms was evaluated. The experimental characterization was focused on the determination of compression, bending, and shear strength. From the results, it is possible to verify that an increase in the moisture content reduces the mechanical strength of the material. The decrease in the values of maximum stress is more significant for moisture values between 12% and the saturation point of the fibers and is accompanied by important dimensional changes that impair the mechanical performance of the material. The results show that above the point of saturation of the fibers the mechanical behavior of the culms is not modified.

Keywords: Bamboo; moisture content; compression; shear; bending

Resumen

Introducción– debido a su comportamiento sismo resistente, el uso del bambú con fines estructurales se ha incrementado en las últimas décadas, principalmente en los países de América del Sur; en los cuales, su empleo, se ha estandarizado en las bases para el diseño estructural. Sin embargo, para el uso eficiente del bambú como material de construcción, es necesario considerar que al ser un material natural, pueden ocurrir variaciones volumétricas, especialmente cuando el material es sometido a cambios en el nivel de humedad entre el punto de saturación de las fibras y el punto de equilibrio de humedad.

Objetivos– El objetivo de este trabajo es evaluar la influencia del nivel de humedad sobre las propiedades mecánicas de los elementos extraídos de las cañas de bambú de la parte inferior, media y superior, con edades comprendidas entre 4 a 6 años, después de inmunizados con una solución de ácido bórico.

Metodología– Para el desarrollo del estudio, se llevó a cabo una investigación con un enfoque cuantitativo. La caracterización experimental se centró en la determinación de la compresión, la flexión y la resistencia al corte, de acuerdo con las recomendaciones de las Normas Técnicas de Colombia (NTC).

Resultados– Los resultados permiten evidenciar que los elementos de bambú son susceptibles de variar su resistencia y rigidez dependiendo de la humedad de equilibrio de la región a considerar en el diseño estructural.

Conclusiones– Se evaluó la influencia del nivel de humedad en las propiedades mecánicas de los elementos extraídos de los culmos de bambú de la parte inferior, media y superior. A partir de los resultados, es posible verificar que un incremento en el nivel de humedad reduce la resistencia mecánica del material. La disminución en los valores de tensión máxima es más significativa para los valores de humedad comprendidos entre el 12% y el punto de saturación de las fibras, y se acompaña de importantes cambios dimensionales que impiden el rendimiento mecánico del material. Los resultados muestran que, por encima del punto de saturación de las fibras, no se modifica el comportamiento mecánico de las cañas.

Palabras clave– Bambú; contenido de humedad; compresión; cortante; flexión

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I. Introduction

Currently, the use of non-conventional materials has gained importance in several areas of civil engineering. The strength of bamboo culms, their low weight, and their hollow cylindrical structure make this type of material a feasible option for the elaboration of structural elements that are subjected to the action of axial and flexural loads during their service life [1]. However, it has been found that as a lignocellulosic material, both the physical and mechanical properties of the material can be noticeably affected when the material is subjected to humidity conditions for prolonged periods [2], [3].

In recent years, the study of the effect of the variations of moisture content on the mechanical performance of structures made from lignocellulosic materials has been reported in the specialized literature [4]-[14]. Mvondo et al. [15], analyzed the effect of moisture content on the tensile and flexural strength of three species of tropical wood: Milicia excelsa, Nauclea diderrichii and Erythrophleum suaveolens, varying the moisture content between 10 % and 30 %. This paper not only demonstrates a loss of mechanical strength with increasing moisture content but also establishes the effect of moisture on the main functional groups present in the wood.

According to Okhio et al. [1], analysis of the influence of the moisture content on bamboo elements may become more complex than for wood elements. This is because in the culms the humidity can vary not only throughout the culm length but also throughout its cross-section [1]. Research results on the physical and mechanical properties of bamboo culms have focused on evaluating the effect of moisture content on the specific weight, dimensional stability, and compressive strength of bamboo culms of the Dendrocalamus giganteus species, analyzing the age of harvest and the conditions of growth (altitude above sea level) [16].

It has been shown that it is possible to degrade the mechanical properties of structural elements when they are subjected to wet conditions for extended periods of time [16], [17]. Xu et al. [18], analyzed the behavior of bamboo culms after their immersion in water for 1 and 7 days, thus simulating the behavior of the material when subjected to the effect of rainy periods. This study showed that with exposure to heavy rains, bamboo elements not only lose mechanical strength but also go from having a fragile behavior to very ductile behavior. On the other hand, Jakovljevic et al. [19], analyzed the influence of the moisture content on the mechanical properties (tensile, compression, and static bending) of bamboos of the species *Pseudosasa Amabilis* and *Pleioblastus Amarus*. The study was based on analyzing the performance of the material after being in a wet chamber for three weeks. The results confirmed that regardless of the type of stress, mechanical strength is significantly reduced when the material has a moisture content of about 60 %.

In Colombia, experimental studies have been carried out during the last decade. In these investigations, the influence of the moisture content on the strength of elements of Guadua culms has been verified [20], [21], [22]. According to Gutiérrez and Takeuchi [20], bamboo elements of Guadua angustifolia Kunth do not exhibit a significant reduction in the tensile strength parallel to the fiber within the range of humidity in which the material is used for structural purposes [20]. However, results presented by Dumar (2014) demonstrate that both the flexural strength and the modulus of elasticity decrease linearly for every 0.01 % that the moisture content in the Guadua angustifolia Kunth increases, when the material is below its proportionality limit [23]. Based on the literature consulted, the present paper presents an experimental methodology for the evaluation of the effect of moisture content on the tensile, compressive and flexural strength of specimens extracted from Guadua angustifolia Kunth bamboo culms, analyzing its influence in the determination of the maximum strength to be used in the earthquake-resistant design of bamboo structures.

II. Materials and Methods

Guadua angustifolia Kunth species were selected, with an average age of 4 years, immunized by injection of a solution of pentaborate and boric acid [21]. The material used comes from the municipality of Calarcá, Quindío. From each of the culm regions, bottom (B), middle (M) and, top (T) sections were cut and labeled as test pieces according to specifications of the Colombian technical standard NTC 5525 [24].

For the variation of moisture content, an immersion method was used. The specimens were previously dried in an oven at a temperature of 102°C for 24 hours or to constant mass condition. They were then submerged in a container with water at room temperature. The immersion time was established by previous tests in which the time was determined to achieve the desired variations in the value of the moisture content.

The determination of the moisture content was performed immediately after completion of the mechanical characterization tests, establishing the mass loss for each specimen, expressed as a percentage of the oven-dry mass, using Equation “(1)”:

$$CH = \frac{w_h - w_s}{w_s} 100 \qquad (1)$$

where

CH is the moisture content, in %

w_h is the mass of the wet specimen, in g

w_s is the mass of the oven-dried specimen, in g

For the determination of the basic density, prismatic specimens were prepared, with an average width of 25 mm, height of 25 mm, and thickness equal to the thickness of the culm wall. The density (mass, oven-dried, per unit of wet or green volume) of each sample was obtained using Equation “(2)”. The volume of the samples in wet or green condition, was determined using the dimensions of the sample according to the procedure recommended in the NTC 5525 [24].

$$DB = \frac{w_s}{V_v} \qquad (2)$$

where
DB is the basic density, in g/cm^3
ws is the mass of the oven-dried specimen, in g
Vv is the wet (green) volume of the specimen, in cm^3.

To determine the FSP, the method proposed by Fuentes (2000) was applied. In this method, the relationship between the volumetric contraction and the basic density was established [25].

The volumetric contraction index from the initial wet condition to the final dry condition and the saturation point of the fibers was calculated according to Equations “(3)”, and “(4)”:

$$ICV = \frac{V_v - V_s}{V_v} \; 100 \qquad (3)$$

$$FSP = \frac{ICV}{0.9\,DB} \; 100 \qquad (4)$$

where
Vv is the wet (green) volume of the specimen, in cm^3.
Vs is the dry volume of the specimen, in cm^3.
ICV is the rate of volumetric shrinkage, in %
FSP is the saturation point of fibers, in %

Table 1. Average dimensions of specimens used in compression test

Specimens	External diameter (mm)	Thickness (mm)	Height (mm)
Top without node	93.60 ± 0.28	13.78 ± 0.72	101.08 ± 0.66
Top with node	97.12 ± 3.7	9.73 ± 2.09	101.09 ± 2.82
Middle without node	106.59 ± 2.43	12.12 ± 0.9	104.53 ± 8.81
Middle with node	110.87 ± 0.73	13.10 ± 0.83	111.86 ± 1.21
Bottom without node	134.35 ± 1.13	14.49 ± 0.27	128.74 ± 1.57
Bottom with node	138.04 ± 0.04	19.95 ± 1.05	136.89 ± 2.71

Source: Authors.

For compression tests, 210 samples of equal length and diameter were prepared. To evaluate the effect of the culm region on strength, 70 specimens were prepared from each of the regions. The geometric properties were measured and are shown in Table 1.

The compression test was performed according the specifications of NTC 5525 [24]. The load was applied at a speed of 0.01 mm/s, until failure occurred. The maximum compression stress was determined according to Equation “(5)”:

$$\sigma = \frac{F}{A} \qquad (5)$$

where
σ is the compression stress, in MPa
F is the maximum compression load, in N.
A is the net cross-sectional area, in mm^2.

For the shear tests, 210 specimens of equal length and diameter ($L = D$) were prepared. The geometric properties are shown in Table 2.

Table 2. Average dimensions of specimens used in shear test

Specimens	Thickness (mm)	Height (mm)
Top without node	9.92 ± 0.33	87.94 ± 0.11
Top with node	10.22 ± 0.26	100.84 ± 0.15
Middle without node	13.56 ± 0.41	105.83 ± 0.17
Middle with node	13.45 ± 0.28	105.76 ± 0.13
Bottom without node	23.19 ± 0.39	136.40 ± 0.09
Bottom with node	23.39 ± 0.24	136.21 ± 0.11

Source: Authors.

For the determination of the maximum strength, a universal test machine was used, in which the specimen was supported at the lower end on two quarters of its surface, applying the load at the upper end on the two quarter parts that were not supported. This way of supporting and applying the load to the specimen produces four cutting areas (see Fig. 1). For the test, the load was applied at a speed of 0.01 mm/s. This test allowed the determination of the maximum load at which the specimen failed, as well as the number of areas that failed. The maximum parallel shear strength was determined according to Equation “(6)”:

$$\tau = \frac{F}{\sum(t * L)} \qquad (6)$$

where
τ is the shear strength, in MPa
F is the applied load, in N
t is the thickness of specimen, in mm
L is the height of the specimen, in mm

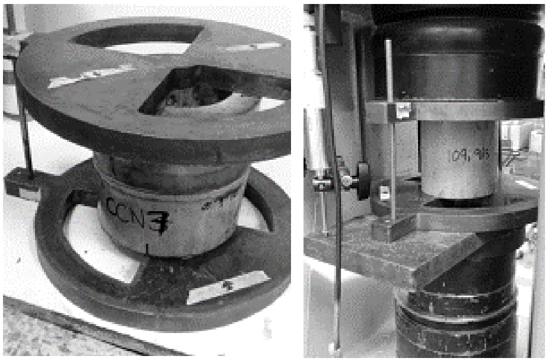

Fig. 1. Shear tests.
Source: Authors.

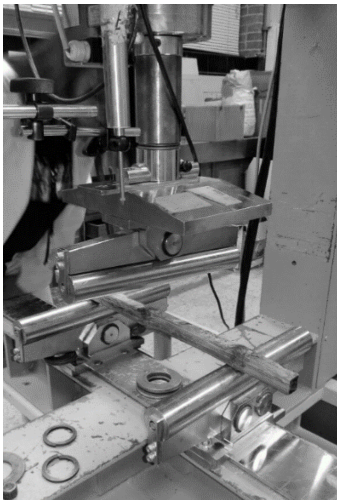

Fig. 2. Static bending tests.
Source. Authors.

For the determination of the modulus of rupture (MOR), a three-point bending test was performed (See Fig. 2). For the test, 150 rectangular beams of 500 mm in length and a square section according to the thickness of the culm region were cut. The beams were selected in order to guarantee the existence of a node in the center of the same (point of application of load) and their supports. The load was applied at a speed of 0.01 mm/s. The physical properties are shown in Table 3. Displacements were measured using a linear variable displacement transducer (LVDT). The rupture modulus (MOR) and the flexural modulus (MOE) were calculated using Equations “(7)”, and “(8)”:

$$MOR = \frac{3FL}{2bd^2} \qquad (7)$$

$$MOE = \frac{FL^2}{4b\delta d^3} \qquad (8)$$

where

F is the applied load, in N
d is the thickness of specimen, in mm
L is the distance between supports, in mm
b is the width of the beam, in mm
δ is the displacement at the middle of span, in mm

TABLE 3. AVERAGE DIMENSIONS OF SPECIMENS USED IN BENDING TEST

Specimens	Thickness (mm)	Width (mm)
Top	9.85±0.45	9.62±0.63
Middle	10.38±0.25	10.49±0.39
Bottom	20.95±0.37	21.30±0.09

Source: Authors.

III. RESULTS AND DISCUSSIONS

The volumetric contraction index and the basic density of specimens extracted from the Guadua culms were determined according to the specifications of NTC 5525 [24]. From the results, it is possible to estimate the saturation point of the fibers (FSP) of the material. The results are shown in Table 4.

TABLE 4. SATURATION POINT OF FIBERS

Region	ICV (%)	DB (g/cm^3)	FSP (%)
Top	10.43±1.36	0.57±0.05	21.26±1.09
Middle	11.74±0.78	0.58±0.02	22.42±1.14
Bottom	13.59±0.83	0.61±0.08	24.78±0.83

Source: Authors.

From the results presented in Table 4, it is possible to see that elements extracted from the bottom of Guadua culms have a higher volumetric contraction index than elements extracted from the middle and top regions (for moisture content below the saturation point of the fibers). Similar results were obtained by Gutierrez et.al [26], and may be associated with the graded functionality of the material [1], [27], [28]. The higher content of parenchymal tissue present in the base of the culms promotes a rapid absorption of water in the material, affecting the performance of material when it is subjected to humid conditions.

In order to analyze the influence of the moisture content on the strength to parallel compression of Guadua culms, graphs of maximum stress were drawn as a function of the moisture content. The results are shown in Figs. 3–8. Average values of representative points obtained during the test are shown in Tables 5, 6, and 7.

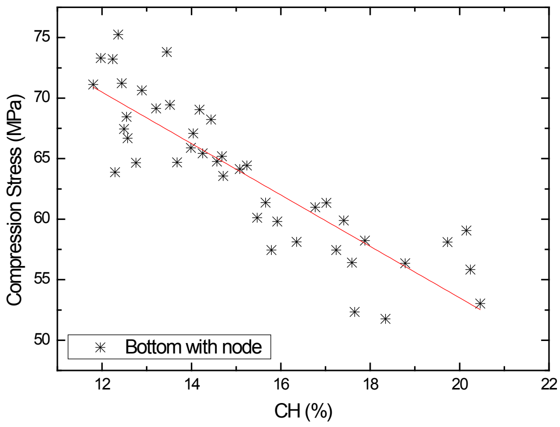

Fig. 3. Variation of compression stress with moisture content in the bottom with node.
Source: Authors.

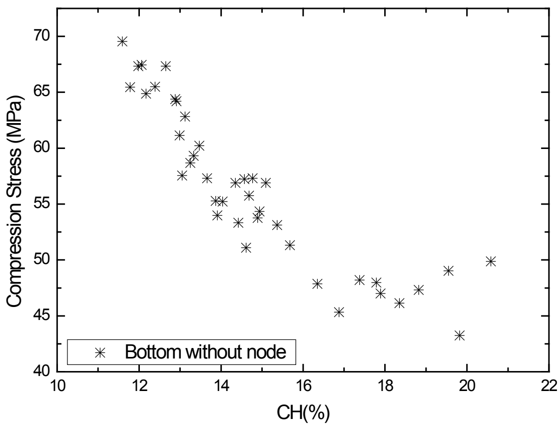

Fig. 4. Variation of compression stress with moisture content in the bottom without node.
Source: Authors.

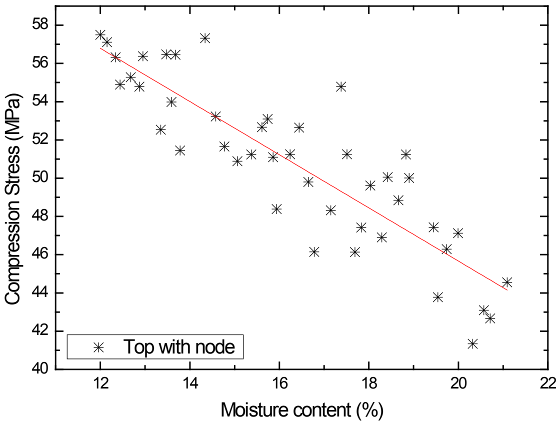

Fig. 5. Variation of compression stress with moisture content in the top with node.
Source: Authors.

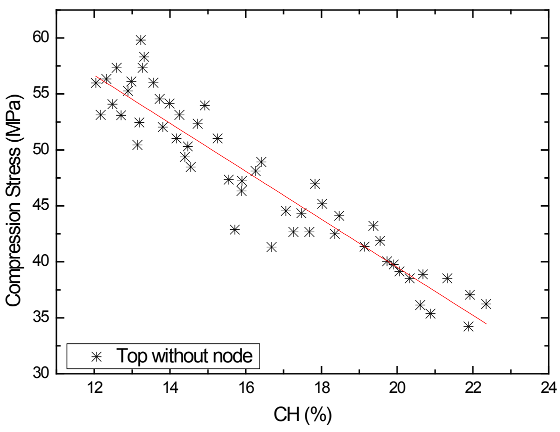

Fig. 6. Variation of compression stress with moisture content in the top without node.
Source: Authors.

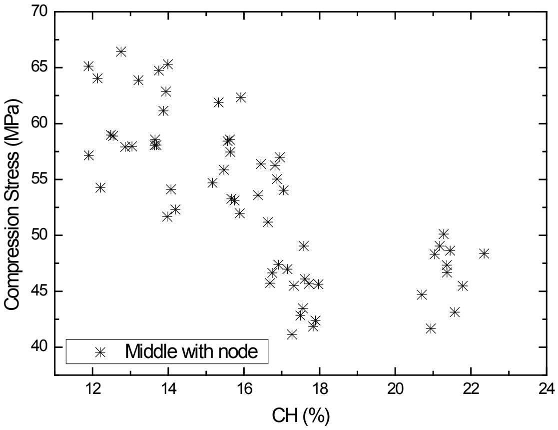

Fig. 7. Variation of compression stress with moisture content in the middle with node.
Source: Authors.

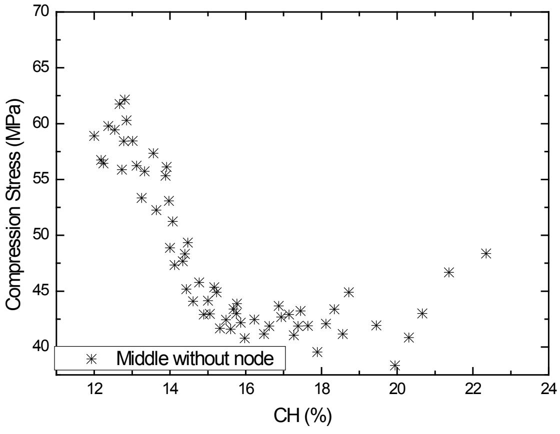

Fig. 8. Variation of compression stress with moisture content in the middle without node.
Source: Authors.

TABLE 5. EFFECT OF MOISTURE CONTENT IN COMPRESSIVE STRENGTH OF BASE REGION (SD IS STANDARD DEVIATION IN MPA)

CH (%)	With node		CH (%)	Without node	
	σ(MPa)	SD (MPa)		σ(MPa	SD (MPa)
12.00-13.30	69.86	8.38	11.60-12.50	65.07	5.86
13.50-14.00	67.32	10.77	12.80-13.60	60.68	6.68
14.01-15.55	66.61	6.00	13.80-15.40	55.40	4.43
16.60-19.00	62.63	8.77	16.00-17.10	53.41	4.27
19.10-21.30	56.23	2.81	19.00-21.00	50.20	6.04
21.50-22.10	52.29	3.66	21.20-23.50	46.41	4.18

Source: Authors.

TABLE 6. EFFECT OF MOISTURE CONTENT IN COMPRESSIVE STRENGTH OF MIDDLE REGION (SD IS STANDARD DEVIATION IN MPA)

CH (%)	With node		CH (%)	Without node	
	σ(MPa)	SD(MPa)		σ(MPa	SD (MPa)
12.00-13.00	60.45	7.86	11.80-12.50	58.91	5.89
13.01-15.00	58.54	5.27	13.00-15.00	54.96	7.14
15.01-16.25	56.70	9.07	15.10-16.00	43.03	6.89
16.50-17.00	52.06	4.16	16.50-18.75	42.41	3.39
17.01-18.00	48.97	6.37	20.50-22.00	42.10	4.63
20.00-22.65	46.69	8.40	22.40-24.00	40.01	4.80

Source: Authors

TABLE 7. EFFECT OF MOISTURE CONTENT IN COMPRESSIVE STRENGTH OF THE TOP REGION (SD IS STANDARD DEVIATION IN MPA)

CH (%)	With node		CH (%)	Without node	
	σ(MPa)	SD (MPa)		σ(MPa	SD (MPa)
12.10-13.00	56.59	8.49	11.10-13.00	55.84	2.79
15.09-16.99	56.54	7.35	13.20-15.00	53.40	3.74
17.70-18.50	50.05	5.51	15.10-16.20	46.42	5.11
18.51-19.60	47.79	4.30	17.00-19.00	44.98	4.05
20.90-22.50	45.51	2.73	21.31-23.00	35.74	2.14
22.70-24.50	42.89	3.43	24.12-25.89	35.12	2.80

Source: Authors

From the results shown in Figs. 3-8, it is possible to observe that when humidity increases between 12 and 23 %, a reduction in the values of compressive strength for the three regions of the world analyzed in this work can occur. This reduction in compressive strength is more significant for intermodal regions (30-35 %) and can be associated with the capacity of absorption of the bamboo parenchyma cells [29].

On analyzing the results shown in Tables 6–8, it is possible to notice a reduction of between 23 and 30 % in the value of the compressive strength in the direction parallel to the fibers when the moisture content increases between 12 % and the point of saturation of the fibers, for base specimens. Similarly, Jiang et al. [30], showed that a reduction approximately of 42 % in the compressive strength of bamboo specimens of the species is possible when the moisture content varies between 12 % and 22 % and allow demonstrating the degradation that occurs in the mechanical strength of the material with an increase in their moisture content.

To analyze the influence of the moisture content on the shear behavior of bamboo, cylindrical specimens were tested. The results are shown in Figs. 9–14.

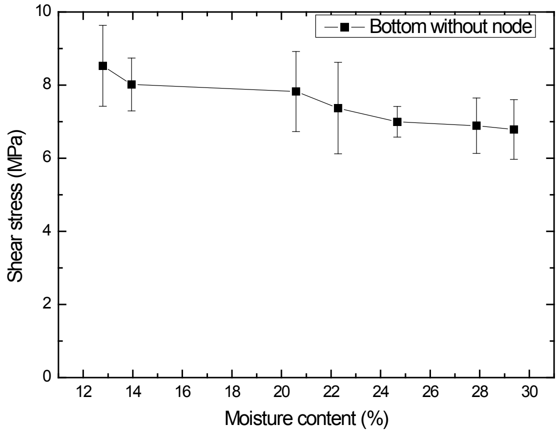

Fig. 9. Variation of shear stress with moisture content in the bottom without node. Error bars represent the standard deviation. Source: Authors.

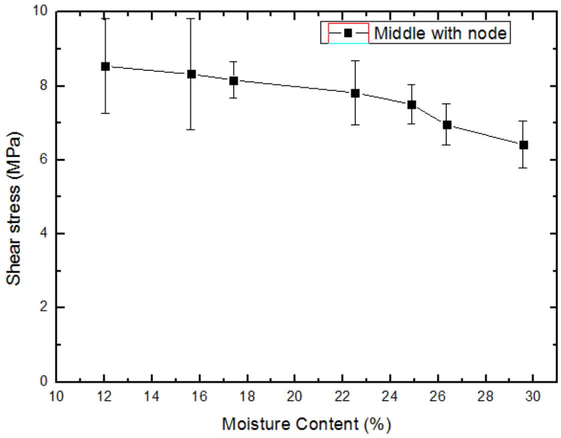

Fig. 12. Variation of shear stress with moisture content in the middle with node. Error bars represent the standard deviation. Source: Authors.

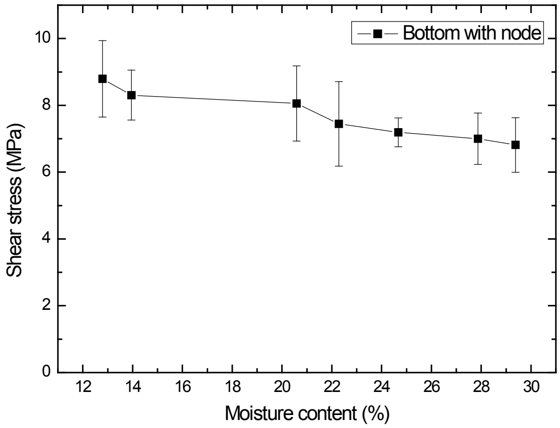

Fig. 10. Variation of shear stress with moisture content in the bottom with node. Error bars represent the standard deviation. Source: Authors.

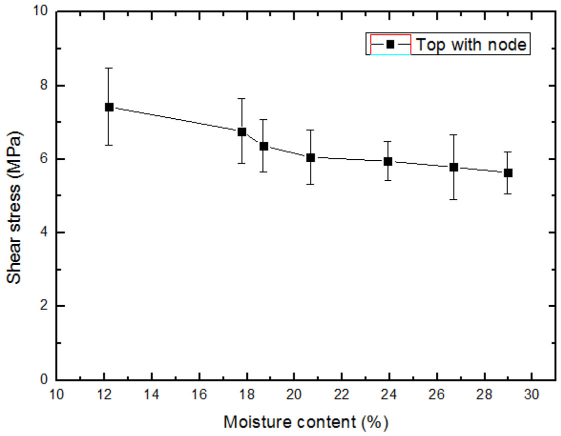

Fig. 13. Variation of shear stress with moisture content in the top with node. Error bars represent the standard deviation Source: Authors.

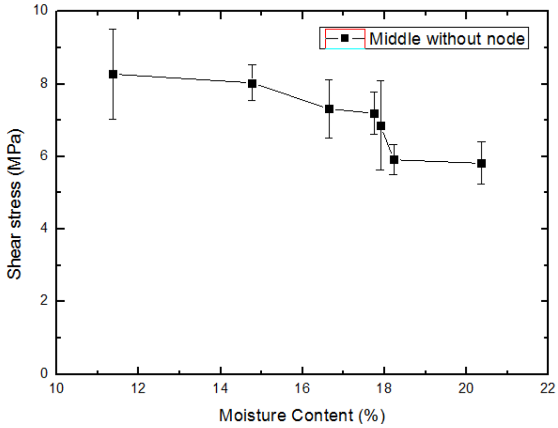

Fig. 11. Variation of shear stress with moisture content in the middle without node. Error bars represent the standard deviation Source: Authors.

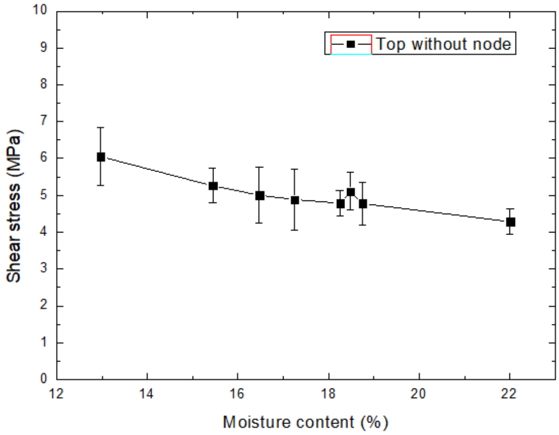

Fig. 14. Variation of shear stress with moisture content in the top without node. Error bars represent the standard deviation. Source: Authors.

From the results presented in Fig.9–14, it is possible to observe a decrease in the shear strength as the moisture content increases. This reduction is more significant for specimens extracted from the top and middle of the culms (25% – 30%). Specimens extracted from the bottom of Guadua culms had a stress reduction of less than 23%. A similar reduction on the maximum shear strength (nearest 30%) was presented by Jiao et.al [30] for the evaluation of the effect of moisture content on the shear strength of Mosó bamboo culms.

Technical results proves that the sensitivity of bamboo specimens to changes in moisture change can be associated with the behavior of each of the culm components (lignin, cellulose and hemicellulose) [31]. Kojima and Yamamoto [32], showed that lignin and hemicellulose are more sensitive to moisture changes than cellulose fibers. Since the shear and compression failure of the material is controlled by the behavior of the matrix, it is expected that when the moisture content approaches the point of saturation of the fibers, the value of the strength will be affected.

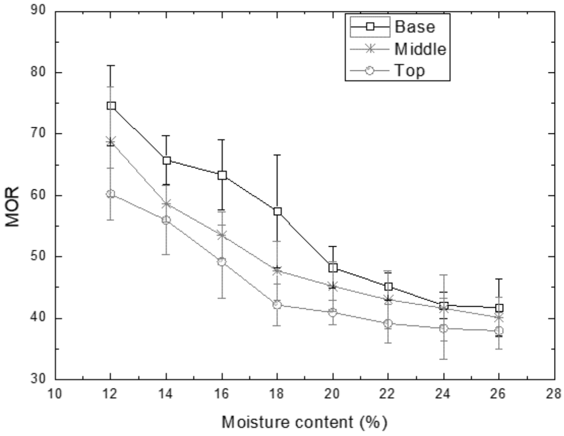

Fig. 15. Results for static bending tests.
Source: Authors.

For the static bending test, center loading across a beam with a span of 300 mm was used (Fig. 15). Fig. 15, shows the variation of the static bending strength for specimens extracted from the top, middle and bottom of the Guadua culms. The results presented indicate a non-linear decrease in the average stress values. Depending on the region of the culms, the reduction in the value of the rupture modulus can be about 45%, when the material has a moisture content close to the saturation point of the fibers. This effect can be associated to the variations that occur in the density of the material, when is exposed to humid environment for a prolonged period of time. Average values of representative points obtained during the test are shown in Table 8.

The effect of the moisture content on the MOE was calculated according eq. (8). The results are shown in Figs. 16-18. Regardless of the culm region, a MOE reduction of approximately 10% can be observed.

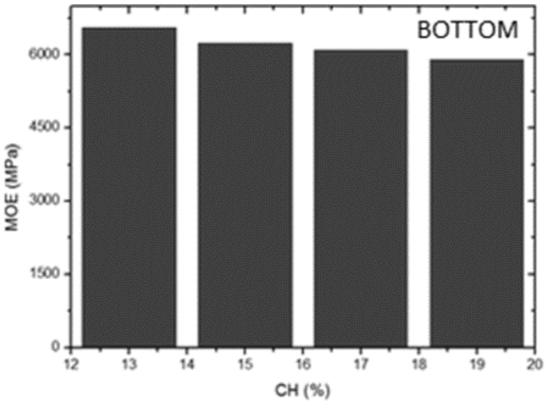

Fig. 16. Effect of moisture content on the MOE (MPa) of the bottom of Guadua culms.
Source: Authors.

Table 8. Effect of moisture content on MOR (SD is standard deviation in MPa)

CH (%)	Base		Middle		Top	
	MOR (MPa)	SD (MPa)	MOR (MPa)	SD (MPa)	MOR (MPa)	SD (MPa)
11.00-12.99	74.64	6.58	68.76	8.94	60.21	4.21
13.00-14.99	65.76	3.95	58.67	2.93	55.94	5.59
15.00-16.99	63.36	5.70	53.50	3.74	4919	5.90
17.00-18.99	57.44	9.19	47.74	4.77	42.14	3.37
19.00-20.99	48.25	3.38	45.21	4.07	40.93	2.05
21.00-22.99	45.17	2.26	43.00	4.73	39.14	3.13
23.00-24.99	42.09	2.10	41.61	5.41	38.32	4.98

Source: Authors.

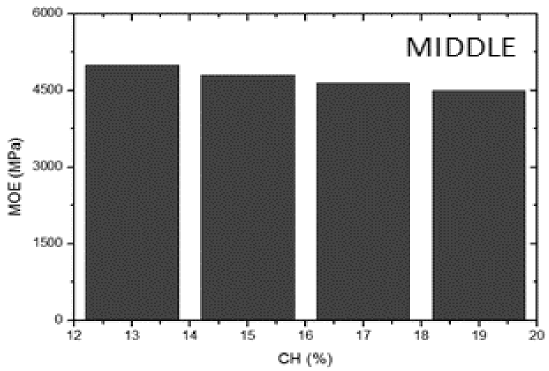

Fig. 17. Effect of moisture content in MOE (MPa) of Middle of Guadua culms.
Source: Authors.

The results presented in Figs. 16–18 show that the variation in moisture content does not cause significant changes in the stiffness of the culms, when the material is subjected to static bending. Similar results was presented by Jiang et al. (a reduction of approximately of 15 %) [30]. The low sensitivity to variations in the value of the flexural modulus could be associated with the typical structure of bamboo culms, principally their cellulose content, principal responsible for the stiffness of culm in static bending test.

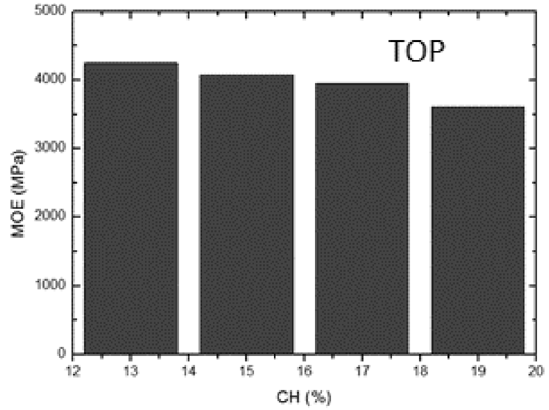

Fig. 18: Effect of moisture content in MOE (MPa) of Top of Guadua culms.
Source: Authors

IV. Conclusions

The influence of the moisture content on the mechanical properties of elements extracted from the bottom, middle, and top of bamboo culms was evaluated. The experimental characterization was focused on the determination of compression, bending, and shear strength.

From the results, it is possible to verify that an increase in the moisture content reduces the mechanical strength of the material. The decrease in the values of maximum stress is more significant for moisture values between 12 % and the saturation point of the fibers and is accompanied by important dimensional changes that impair the mechanical performance of the material. The results show that above the point of saturation of the fibers the mechanical behavior of the culms is not modified.

V. Recommendations

It is recommended for future work to analyze the influence of moisture variation on the microstructure of Guadua elements and the development of a numerical model that can predict the behavior of bamboo elements in relation to the equilibrium humidity of the principal regions of Colombia.

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